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NASA PROGRESS REPORT

SPATIAL CHARACTERIZATION OF ACID RAIN STRESS IN CANADIAN SHIELD LAKES

NASA Contract: NAS5-28779

Principal Investigator: Fred J. Tanis

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1.0 OBJECTIVE

The acidification of lake waters from airborne pollutants is of continental proportions both in North America and Europe. A major concern of the acid rain problem is the cumulative ecosystem damage to lakes and forest. The number of lakes affected in northeastern United States and on the Canadian Shield is thought to be enormous. Our principal research objective is to examine how seasonal changes in lake transparency are related to annual acidic load. Further, the relationship between variations in lake acidification and ecophysical units is being examined. Finally, the utility of Thematic Mapper (TM) based observations to measure seasonal changes in the optical transparency in acid lakes is being investigated.

Previous investigations have suggested that dissolved organic carbon (DOC), which originates from the dissolution of humic substances, controls transparency in most Canadian Shield Lakes. It has also been

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established that aluminum, which is abundant in the local rocks and soils, is easily mobilized by acidic components contained in spring runoff. The presence of any significant amount of aluminum induces a loss of DOC from the water column by coagulation, resulting in increased optical transparency. This process has not been observed in normal lakes associated with buffered geologies. In a normal lake, transparency would tend to decrease in time with seasonal phytoplankton productivity cycles. Thus seasonal changes in the optical transparency of lakes should potentially provide an indication of the stress due to acid deposition and loading.

The potential for this optical response is related to a number of local ecophysical factors with geology being, perhaps, the most important. Other important factors include sulfate deposition, vegetative cover, and terrain drainage/relief. The area of southern Ontario under study contains a wide variety of geologies from the most acid rain sensitive granite quartzite types to the least sensitive limestone dolomite sediments. Annual sulfate deposition ranges from 1.0 to 4.0 grams per square meter.

2.0 APPROACH

Water quality parameters are being measured along with insitu optical data in representative lakes in the Canadian Shield. This is being done to calibrate a Bio-Optical Model which defines the linkages between the acid rain induced chemical lake processes and the upwelling radiometric signals as measured by the Thematic Mapper sensor on Landsat. A spring/summer scene pair with companion field measurements is being collected in selected study sites located in northern Ontario. These data will be used to investigate possible formulations of the multitemporal, remotely sensed causal relationships between pH and observed changes in water transparency.

It is hypothesized that a verifiable relationship exists between seasonal changes in water quality associated with the level of lake acidification and Thematic Mapper radiometry. The verified Bio-Optical Model will be used to establish the limits for which such relationships are inherently valid, and together with the field data, the set of ecophysical units and water quality conditions where the Landsat approach is valid. Under these restrictions lakes within an ecophysical stratum will be assigned a value for the degree of acidification based upon the TM multitemporal relationship. These results will permit one to test the hypothesis that the severity of lake acidification is not uniform over large areas, but rather that variations exist which are strongly related to ecophysical units and proximity to probable sources of atmospheric inputs.

3.0 ACTIVITIES BY TASK

3.1 Stratification of Ecophysical Parameters (Task 1)

The Canadian Shield area covered by three Landsat TM scenes has been stratified into ecophysical units based upon soil/bedrock sensitivity, vegetative cover, terrain/drainage, and acid deposition. The objective of the stratification is twofold. First, it is intended to reveal the location, status and co-occurrence of environmental attributes which influence lake acidification. Second, it provides a basis to characterize each lake within the study areas as an aid to the sampling design. Landsat scenes with overlays of polygon boundaries are shown as Figures 1 and 2 for Landsat TM scenes 22-27 and 19-27 respectively.

The strata definitions were based upon a simple linear combination of the four ecophysical indicators where the submodel rating was multiplied by the appropriate weighting coefficient. Initial clustering results were based upon a (0.4) weight for acid deposition and a (0.3) weight for soil/bedrock, a (0.2) weight for vegetation, and (0.1) for drainage. Seven of the ten resulting clusters were found to be significantly different. A few sets of coefficients were tried in an effort to improve the clustering results. A clustering which was found to improve significance was based upon a greater weight for soil/bedrock sensitivity and a corresponding decrease for acid deposition. The following coefficients were used: soil/bedrock (0.4), vegetation (0.3), drainage (0.1), and acid deposition (0.2). The F ratio, and significance, for the entire clustering increased with this change in coefficients from 327 to 3020. In this latter case each of the ten clusters produced were found to be significantly different. The ten clusters are related to the indicator parameters by the following descriptions.

Cluster 1 is characterized by shallow sandy soils over rock types 3 and 4 as described below with less than 50% outcropping. Vegetative cover is a mixture of conifers and hardwoods with a dominance of the hardwoods. The terrain is level to rolling. The average acid deposition is approximately 2.0 $g/m^2/yr$.

Cluster 2 is characterized by moderate depth soils over rock type 4 with less than 50% outcropping. Vegetative cover is a mixture of conifers and hardwoods with a dominance of the hardwoods. The terrain is level to rolling. The average acid deposition is approximately 2.5 $g/m^2/yr$.

Cluster 3 is characterized by deep sandy soils over rock type 4 with less than 50% outcropping. Vegetative cover is a mixture of conifers and hardwoods with a dominance of the hardwoods. The terrain is level to rolling. The average acid deposition is approximately 2.5 $g/m^2/yr$.

Cluster 4 is characterized by moderately deep soils over rock type 4 with less than 50% outcropping. Vegetative cover is a mixture of conifers and hardwoods with a dominance of the hardwoods. The terrain is level to rolling. The average acid deposition is approximately 2.25 $g/m^2/yr$.

Cluster 5 is characterized by moderately deep sandy soils over rock type 4 with less than 50% outcropping. Vegetative cover is a mixture of conifers and hardwoods with a dominance of the hardwoods. The terrain is level to rolling. The average acid deposition is approximately 2.75 $g/m^2/yr$.

Cluster 6 is characterized by deep clay soils over rock type 3 with less than 30% outcropping. Vegetative cover is mostly hardwood. The terrain is level to rolling. The average acid deposition is approximately 2.25 $g/m^2/yr$.

Cluster 7 is characterized by shallow sandy soils over rock type 4 with less than 50% outcropping. Vegetative cover is a mixture of conifers and hardwoods with a dominance of the conifers. The terrain is level to rolling. The average acid deposition is approximately 2.5 $g/m^2/yr$.

Cluster 8 is characterized by moderately deep sandy soils over rock type 3 with less than 50% outcropping. Vegetative cover is a mixture of conifers and hardwoods. The terrain is level to rolling. The average acid deposition is approximately 2.0 $g/m^2/yr$.

Cluster 9 is characterized by shallow sandy soils over rock type 4 with less than 25% outcropping. Vegetative cover is dominated by conifers. The terrain is level to rolling. The average acid deposition is approximately 2.5 $g/m^2/yr$.

Cluster 10 is characterized by deep sandy soils over rock types 3 and 4 with less than 50% outcropping. Vegetative cover is a mixture of conifers and hardwoods with a dominance of the hardwoods. The terrain is level to rolling. The average acid deposition is approximately 1.5 $g/m^2/yr$.

These clusters are separated by only small changes in the mean value for each indicator. The range of polygons within each cluster frequently exhibits the entire range of each indicator. None the less the clustering process classifies each the above environmental descriptions to be significantly different.

The bedrock sensitivity classes were defined by Environment Canada, Lands Directorate, on the basis of lithology and are grouped according to their potential to reduce acidity.

Type 1: Limestone, marble, and dolomite.

Type 2: Carbonate siliceous sedimentary: shale, limestone/noncalcareous siliceous with carbonate interbeds: shale, siltstone, dolomite, quartzite sandstone with carbonates.

Type 3: Ultramafic rocks, sepentine/noncalcareous siliceous sedimentary rocks: black shale, slate, chert/anorthosite: gabbo, diorite/basaltic and associated sedimentary: mafic volcanic rocks.

Type 4: Granite, gneiss, quartzite sandstone, syenitic and associated alkalic rocks.

3.2 Site Selection (Task 2)

Site selection was based upon the stratification and clustering analysis described above and each of the following considerations: (1) availability of historical water quality and possibly remote sensing data, (2) existing Canadian initiatives to collect site specific data, (3) accessibility, and (4) coverage of ecophysical lake types. Sites selected included (1) Algoma, (2) Sudbury, (3) Wawa, and (4) Dorset.

3.2.1 Sudbury Site

Location: The Sudbury Site is located within the Landsat TM scene Path 19-Row 27 and has the following coordinates:

Upper Left: 47^0 40.05' W80^0 49.40'
Lower Right: 46^0 16.51' W80^0 36.50'

Geology: The geology of the Sudbury site is dominated by the Lorrain formation which consists of quartzite, arkose, quartz sandstone, micaceous and aluminous quartz sandstone, quartz feldspar sandstone, and minor conglomerate and siltstone. Mafic intrusive diabase and granophyte dikes and sheets are distributed evenly throughout the site except near lake Wanaptei Significant amounts of conglomerate, sandstone, siltstone and argillite are found in the southern half and northern tip of the site. In addition scattered areas of felsic intrusive and metamorphic rocks, and felsic to intermediate metavolcanics occur.

Vegetation: Approximately 65% of the test site has conifer forest cover and approximately 35% is classified as mixed forest.

Sensitivity: Approximately 90% of this site has low potential to reduce acidity and the soil is predominantly shallow. The remaining 10% of the site has a moderate potential to reduce acidity with shallow soils and ultramafic bedrock.

Acid Deposition: Annual deposition in 1982 was 1.24 g/m^2 of sulfate

3.2.2 Algoma Site

Location: The Algoma site is located within the TM scene 22-27 and has the following coordinates:

Upper Left: 47^0 21.5', W84^0 25.8'
Lower Right: 47^0 00.0', W84^0 13.8'

Geology: Granitic rock predominates (60%) in the Algoma site and is concentrated in the northeast and southwest corners. Approximately 25% of the geology consists of acid to intermediate metavolcanics and 15% is basic and undifferentiated metavolcanics. Several lakes are situated in greywacke-slate-arkose and grabbro formations.

Vegetation: Hardwood forests predominate (Sugar Maple, Birch, Trembling Aspen) with a few mixed stands in the lowland areas (White Birch, Black Spruce, and White Spruce).

Sensitivity: the northern half (approximately 55%) of the site has a high sensitivity to acid deposition with 0.25 to 1 meter soil depth of sandy texture and granite and associated alkalic bedrock. The southern corner(5%) is the same as the northern half of the site. A moderate potential to reduce acidity is found in the southern part of the test site (35%), which stems from a differing bedrock (ultramafic serpentine, non-calcareous silicic sediments and anorthosite)

Acid deposition: Annual deposition of sulfate 1.5-2.0 g/m^2

3.2.3 Dorset Site

Location: the Dorset site is located near the southern edge of TM scene Path 18-Row 28.

Geology: Acid intrusives occur throughout this area including granite, syenite, granite gneiss, grantized sedimentary and volcanic rocks.

Vegetation: Predominantly hardwoods (Sugar Maple, Red Maple, Yellow Birch, Trembling Aspen) occur in this area. Hemlock and Eastern white pine are found in selected areas.

Sensitivity: The Dorset area is in the center of a large region of high deposition. West of Dorset there is less than 50% exposed bedrock and to the east 50 to 75% is exposed.

Acid Deposition: Annual deposition of sulfate 2.90 g/m^2

3.2.4 Wawa Site

Location: The Wawa site is located northeast of Wawa, Ontario near Michipicoten Bay.

Geology: The northern third of the Wawa site consists of mafic metavolcanics. Felsic metavolcanics occur in the southern tip of the site and are also interspersed with metasediments (conglomerate, greywacke, shale, arkose, and quartzite) near the middle of the site.

Vegetation: This site contains large non-vegetated areas which have been impacted by the smelter fumes from Wawa.

Sensitivity: This area is moderately sensitive to acid deposition. A small area of high sensitivity exists along the Maple River in the southern part of the Wawa plume.

Acid Deposition: Annual deposition in 1982 was 1.5 g/m^2

3.3 Liaison Activities with the Canadians (Task 3)

A cooperative program with Canadian agencies and Universities interested in the remote sensing aspects of the acid rain problem have resulted in an informal joint program which includes four major Canadian participants. These are Professor Roger Pitblado of Laurentian University Sudbury, Ontario, Dr. John Fortescue of the Ontario Geological Survey (OGS), Dr. Vernon Singroy of the Ontario Centre for Remote Sensing (OCRS), and Professor Michael Dickman from Brock University, Saint Catherines, Ontario. The Canadians are funded by the Ministry of Environment (MOE) and the Ontario Geological Survey.

A meeting was held on 27 May 1986 to discuss a preliminary program plan. John Fortescue announced that the Canadians participants were now funded at 200K for a one year period to work collaboratively on the program. These monies were budgeted to equally support remote sensing data collection and analysis, and a geochemical survey.

The Canadian effort was based on meeting two separate but highly complementary objectives. The OGS objective was designed to look at the relationships between environmental and geochemical studies involving lake acidification and remote sensing. The geochemical survey techniques developed by John Fortescue of the OGS involve analysis of chemical constituents in lake water samples and in bottom sediment cores. A mineral resource appraisal was a specific objective of the OGS component. The MOE support was directed at examining the role remote sensing can play in the study of lake acidification in both the short and in the long term. The MOE had stressed that effort be placed on the Sudbury site where there exists an extensive limnological data base. The MOE plan includes examination of several historical Landsat TM and MSS collections. The Canadian program recommended use of two sites one at Algoma and one at Sudbury, Ontario, each comprising approximately 1000 sq. km. Priorities were set for each of the four collection sites based upon group interests and availability of resources. First priority was given to the Sudbury site, second to Algoma, and third to Wawa. The Dorset site was viewed to be largely beyond the reach of a one month field program and would only be addressed after the other data objectives had all been met. A lake sampling budget of approximately 300 samples was divided between the first three sites with 150 samples allocated to Sudbury, 130 allocated to Algoma, and 20 to Wawa. An additional 25 samples would be taken to support the Dorset sampling if resources were available.

The ERIM field plan specified sampling at three different scales and with three different optical measurements. First, Landsat TM data were to be collected from each site coincident with the field work, providing coverage of the entire site and more specifically each sample lake. Second, a helicopter-based spectroradiometer (PROBAR) was to be used to collect radiometric data in each of 15 narrow spectral bands, at the center of each sample lake. Lakes to be sampled with the PROBAR were limited to those large enough to be visible in TM imagery and sufficiently deep not to produce a bottom reflected signal. The PROBAR unit has been rented from Moniteq Ltd., Toronto, Ontario and can be controlled with an IBM PC which also must be mounted in the helicopter. The PC logs the radiometer data and allows easy transfer to the DEC VAX780 for data analysis. Third, a subsurface spectroradiometer (Biospherical Inc. MER-1000) and a transmissometer (SEATECH Inc.) were used to characterize the optical properties in a few of the PROBAR sampled lakes. The strategy in this three-tier sampling scheme is to develop a model/relationship from the insitu optical measurements and the measured limnological parameters. This "optical response model", once validated, will be extended to the PROBAR data set and finally to the Landsat data set where it will aid the interpretation of TM observations.

3.4 Define Multitemporal Radiometric Relationships to Acidification (Task 4)

In this task a TM radiative transfer model will be calibrated to predict possible temporal changes in signal level which result from field-measured changes in optical and chemical properties. Work has proceeded on this model to include specific calibration for the Landsat TM sensor. The model treats atmospheric optics, water optics, and the wind ruffled air-water interface. A solar emphemeris model has also been implemented to provide a capability to simulate the entire sun/sensor geometry. It is planned that subsurface optical measurements in the field will be supplemented with optical parameters derived by Bukata [1986] for Ontario Lakes.

3.5 TM Data Processing (Task 5)

The extraction software has been applied to an historical TM scene (22-27) for the Algoma site. Brightness values were extracted from the approximate center of each lake based upon the latitude and longitude of each lake center. A 3 x 3 pixel area was extracted and the mean brightness in each band was recorded. These extracted mean values were then correlated to historical water chemistry data available for the same lakes. There were very few lakes in this set with reported values of dissolved organic carbon and chlorophyll-a pigment concentration. Largest correlations were found with reported Secchi depth transparency.

3.6 Determine Relationships with Field Data (Task 6)

In this task the relationships that exist between lake water-quality, optical measurements, and seasonal changes in TM radiometry with lake acidification will be determined. An historical water quality data base has been obtained from the Ministry of Environment for all of Ontario, which contains many lakes within our proposed field sites. A second data base is being acquired for approximately 200 lakes in the Sudbury area, many of which are located within the proposed sampling site. The most important parameters within this data base are those which have impact on the optical transparency of the water. These are chlorophyll pigments, suspended mineral particles, and dissolved organic carbon. Of these DOC is considered to have the greatest influence on optical properties in Northern Ontario. Secchi depth transparency or any other measures of transparency are regarded to be highly correlated to DOC, especially in lakes where the other components have minimal influence. Because of the possible chemical ties between DOC and aluminum, the presence of aluminum may also have an "optical" signature.

Several investigators including Almer [1974], Malley [1982], Schofield [1972], and Yan [1983] have reported a reduction in attenuation with acidification. Almer proposed that the changes resulted from probable interaction between aluminum mobilized in the watershed and DOC, and argued that an aqueous solution with pH below 5 will result in the precipitation of humic substances (as DOC) from the water column. At pH's above 5.5 the aluminum, as aluminum hydroxide, will precipitate from the water column. The concentration of soluble aluminum will increase significantly if watershed soils are acidified and thus there seems to be a strong relationship between dissolved aluminum and lake pH. Acidified lakes with high concentrations of aluminum should also be relatively clear because of the complexing reductions of DOC. Almer, however, suggests in lakes with very high humus the aluminum complexing does not result in precipitation. Effler's [et.al., 1985] description of experiments in Dart Lake not only confirm the strong relationship between DOC and lake transparency but also demonstrate the coagulation/adsorption of DOC by aluminum. Also, Effler measured a temporal increase in transparency from May to September with a corresponding decrease in epilimnionic aluminum and DOC concentrations.

Some historical data collected by John Fortescue at OGS, using the helicopter-based PROBAR over a portion of the Algoma site, were made available to be analyzed with coincident limnological data. These data were collected on August 22, 1984 and on September 6, 1985. Fortescue had attempted to used these data to separate clear and colored acidic and normal pH lakes within the site [Fortescue, 1986]. Since many of the same lakes were to be sampled during the planned August field work using the PROBAR radiometer, it seem reasonable to examine these data for potential relationships between the PROBAR measurement in TM bands and the measured values of DOC, pH, etc. The data set consisted of 113 sample locations and a representative subset was selected for data reduction. The reported reflectance at 10nm intervals were first reduced to simulate TM band reflectance in bands 1 through 4. These data were then statistically correlated to the available limnological data.

Attempts to run analyses on a combined 1984-1985 data set yielded very poor correlations. It was determined that the PROBAR data from the two years could not be correlated by TM band. The 1985 data were found to be suspect because of reported instrumentation problems and further analysis of the 1985 PROBAR data set was therefore discontinued. The pH values of the 1984 data set ranged fro 4.9 to 5.57 with a mean value of 5.24. DOC values were high and ranged from 3.1 to 14.1 mg/l with a mean value of 6.7 mg/l. Resulting correlations with estimated TM reflectance values were considered modest with the largest correlations coefficients found of -0.73 and -0.71 between pH and TM bands 3 and 4 respectively. Similarly coefficient of 0.62 and 0.64 were determined between these TM bands and measured DOC. Correlations of comparable magnitude were observed between pH, DOC, and Secchi depth transparency. These same parameters were essentially uncorrelated to estimated reflectances in TM bands 1 and 2. The lack of strong correlations was attributed to the relatively high levels of DOC which all but totally absorb the radiation in TM bands 1 and 2.

3.7 Spatial Aspects of Acidification (Task 7)

An analysis will be performed to interpret the spatial aspects of lake acidification. In this task each lake within an ecophysical stratum will be assigned a value based upon a TM multitemporal acidification relationship. These values will be used to assess the significance of atmospheric inputs, and the level of acidification, in relation to ecophysical parameters. Currently no work is being performed on this task.

4.0 TECHNICAL PROBLEMS

Some minor technical problems have occurred with the reading of Canadian TM data obtained from the Canadian Centre for Remote Sensing. These problems pertained to incomplete and non-standard format for the header file. The EROS software is being modified to accommodate reading of the Canadian data.

5.0 PLANS FOR THE NEXT REPORTING PERIOD

The initial collection of field data will begin during the first part of the next period. Plans call for the collection of field data during the month of August including several Landsat TM acquisitions. Field data will be reduced after the field trip and data will be exchanged with the Canadian investigators.

6.0 REFERENCES

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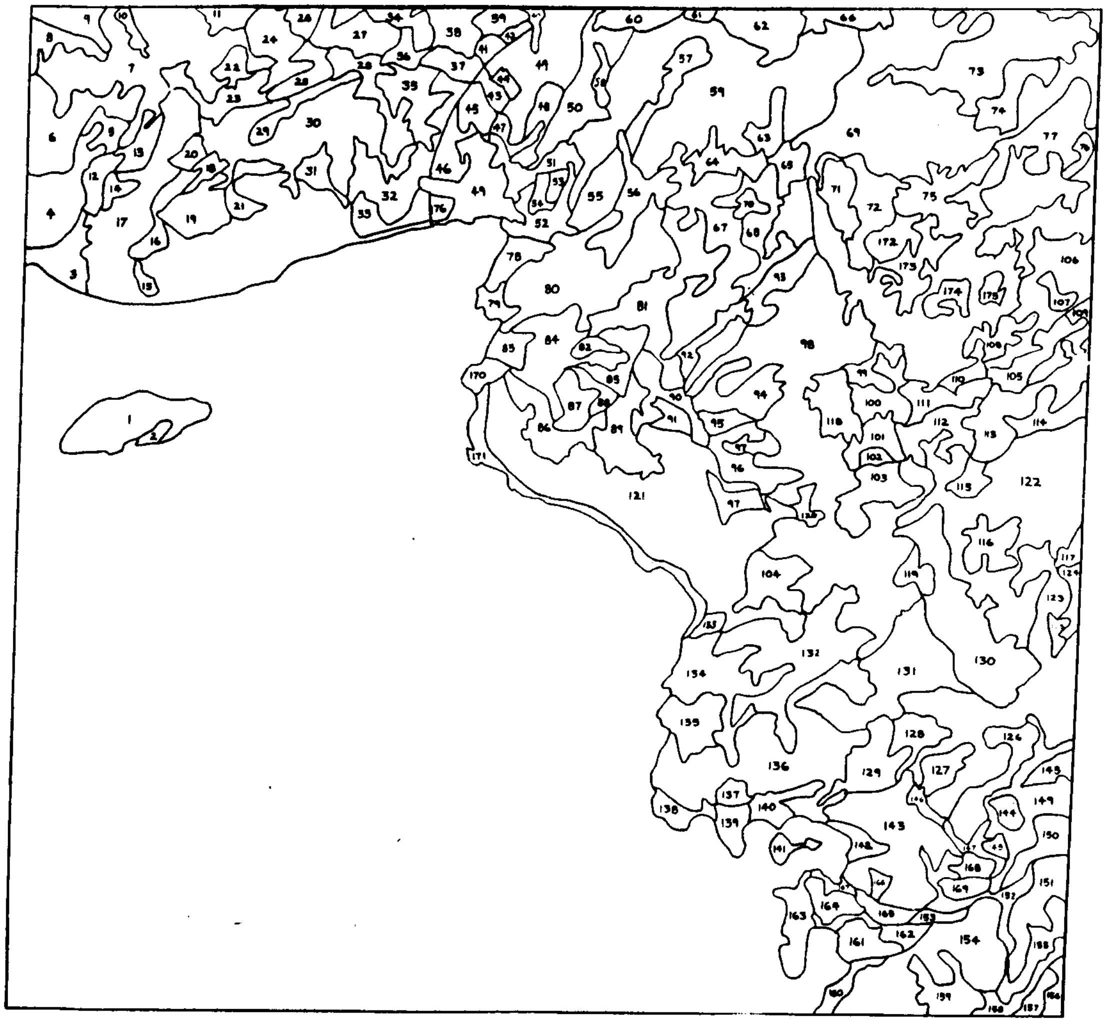
FIGURE 1. THE ALGOMA AREA

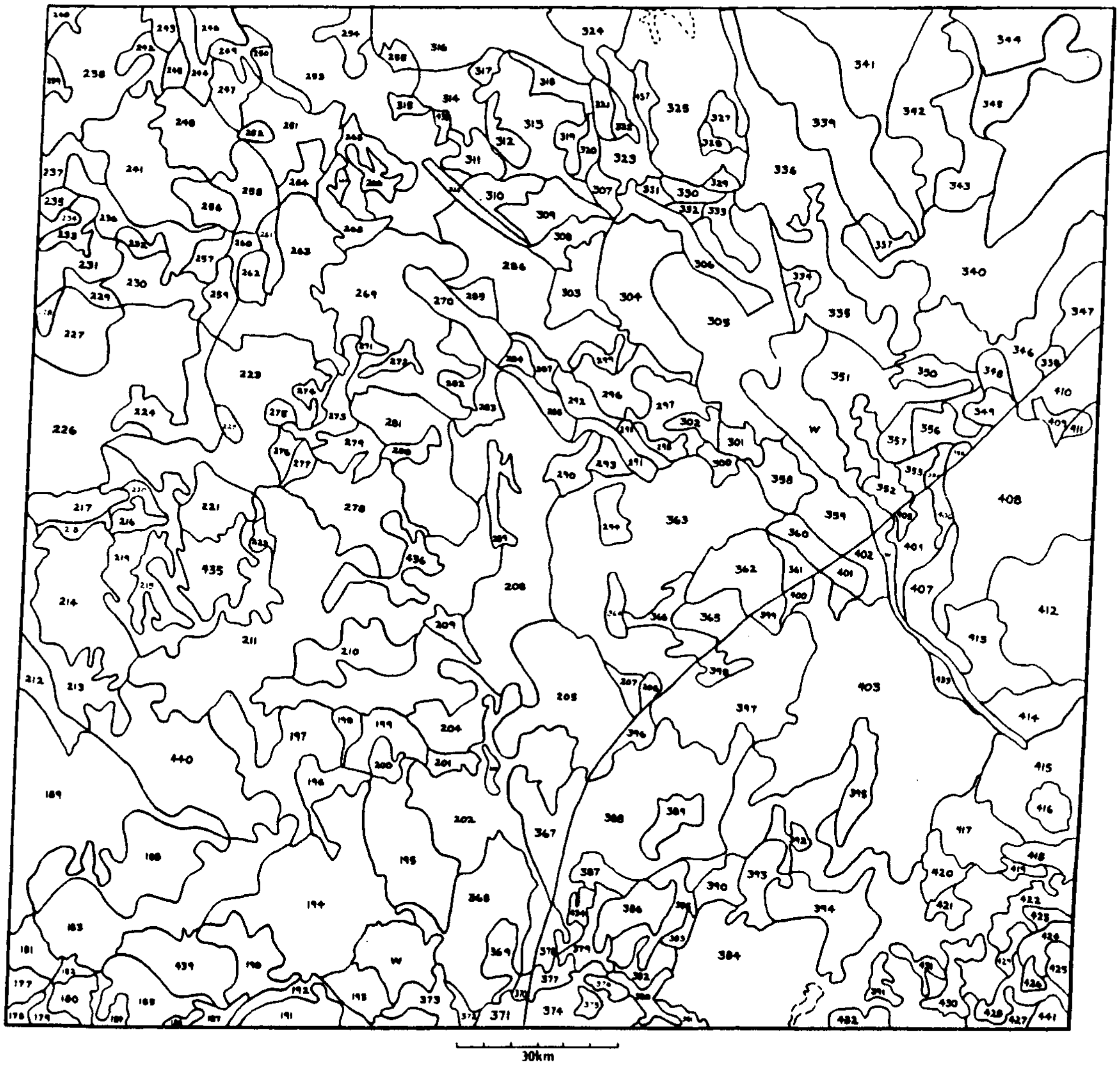


30 km

The Polygon Overlay Corresponds to the Area Covered by Landsat 4/5 (TM) Path 22, Row 27.

ORIGINAL IN COLOR

FIGURE 2. THE SUDBURY AREA



The Polygon Overlay Corresponds to the Area Covered by Landsat 4/5 (TM) Path 19, Row 27.